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Scaling Issues in the Determination of Wind Loads on Lattice Masts

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ABSTRACT: The paper presents a study conducted to investigate the influence of geometric scale and flow condition on the wind load coefficients for lattice masts structures. An initial study in 2008 on a full size mast section indicated a possible contingency, which could be used to add equipment on telecommunication towers without further structural strengthening. This study focuses on the role of scaling. A 1:6 scaled mast model was tested in two different flow conditions and in three layout variations. It was found that scaling does play a large role and that some of the codified loads are in fact more reflecting model scale behavior than full scale aerodynamics. This reveals the main challenge if for reasons of economic production and operation of telecommunication towers and masts a more accurate wind load description is required: full size testing.

KEY WORDS: ICWE14; wind loads; wind tunnel testing; scaling; lattice masts; circular tubes; Reynolds effect; drag coefficient.

1 BACKGROUND

Over the last years the special attention was paid to wind loading on lattice structures, in particular on telecommunication masts and towers. Extreme storms caused significantly less structural stress or even damage than expected. This lead to the question whether the characteristic wind load coefficients provided by codes and standards are conservative leading to a significantly over-dimensioned structural resistance. From the telecommunication industry point of view this over-dimension could provide a basis of increasing the allowable amount of equipment on existing masts without structural strengthening. On the other hand masts and towers could potentially be manufactured with less material. To effectuate a possible increase of tower payload or material savings the margin between the assumed loads from codes and the actual acting loads needs to be determined accurately.

In 2008 wind tunnel tests on full-scale lattice mast sections have been performed and compared to load predictions from literature and in particular from design codes [1]. The results revealed a clear difference indicating that codified loads are noticeably higher hence supporting the hypothesis of over dimensioned mast structures. Wind loads have traditionally been determined through wind tunnel testing at reduced scale where the establishment of similarity between experiment and nature is the key for a reliable estimation of load action and action effects. However, aerodynamic forces on circular cylinders are due to the Reynolds effect sensitive to scaling and the obtained data may be biased because of experimental boundary conditions constraining fluid mechanical similarity. In the discussion prior to the 2008 study it was suggested that a substantial part of codified load coefficients derive from a wind tunnel study on lattice masts performed in the 1970ies at the National Maritime Institute (NMI) in the UK. For this reason a reconstruction of the NMI test was included in this study to relate the results from the scaling effect study to the codified loads by estimating the comparability of the experimental boundary conditions.

Hence, the study presented in this paper has two main objectives, namely the scaling effect on load coefficients used for structural design of telecommunication towers and secondly the comparability of the performed study to the tests modern codes and standards are supposedly based on.

2 PREPARATION & DEFINITIONS

2.1 Model configurations

Two different mast types were tested in the study: the first is a replica of a mast design tested by the National Maritime Institute (NMI) in the UK in 1977 [2] and the second is a scaled version of the mast tested as full size prototype in 2008 [1] at the VELUX wind tunnel in Denmark. The latter has been studied in three variations: (1A) naked mast structure, (1B) with ladder and (1C) with ladder and feeders attached to the mast. The prototype mast was provided by the Danish company Rambøll.

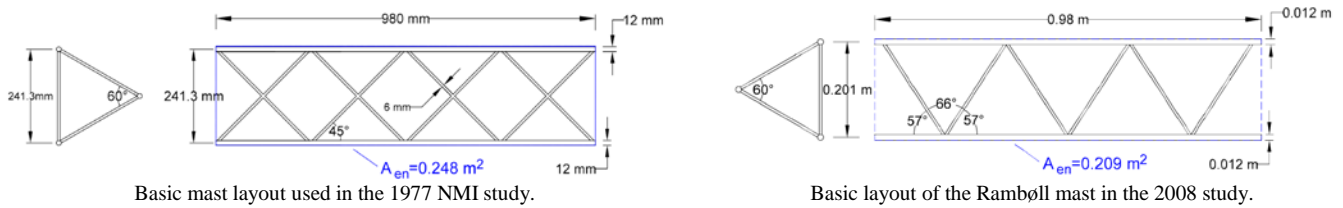


Figure 1. Fundamental mast designs (types) tested in frame of the study. All measures are in model scale.

The comparison of load coefficients of the same mast configuration from full- and model scale shall allow concluding on the magnitude of scaling effects. Reconstructing the NMI tests shall give some insight on the models design and hence on the consideration of scaling effects in the results.

Table 1. Geometric data of the mast models used in the wind tunnel study.

	NMI mast type		Rambøll mast type	
	original	replica	prototype	1:6 model
Structural members:				
- Chord	Ø12.7 mm	Ø12 mm	Ø76.1 mm	Ø12 mm
- Bracing (tubular)	Ø6.35 mm	Ø6 mm	Ø33.7 mm	Ø6 mm
Ancillaries:				
- Ladder chords	-	-	Ø33.7 mm	Ø6 mm
- Ladder steps	-	-	Ø20 mm	Ø3 mm
- Cable supports	-	-	U35x23x3 mm	5x5 mm
- Cables (feeder)	-	-	8xØ3/8"	8xØ2 mm ¹⁾

¹⁾To achieve similar aerodynamic drag combinations of Ø2 mm and Ø1 mm tubes have been used for the feeders.

Table 1 gives the measures of the models and full size structures. For the manufacturing of the models available off-the-shelf material was used leading to small deviation from the ideal geometric scale. All scaled models are made of steel.

2.2 Facility & flow conditions

The wind tunnel tests were conducted in the Climatic Wind Tunnel (CWT) [3] at the Department of Hydro and Aerodynamic of FORCE Technology in Denmark. Facility development and research activities are a joint effort between FORCE Technology and DTU. The wind tunnel has a closed air circulation running about 32m/s at maximum airspeed (smooth flow with an along wind turbulence intensity of about $I_u = 0.6\%$). The test section has a cross-flow dimension of 2m x 2m and an overall length of 5m. The mast models were mounted horizontally right in the centre of the test section (Figure 2, left). The section models are about 1m long and are suspended between two end plates. The aerodynamic loading was measured with two force balances located on each side of the model between end plate and wind tunnel wall. Model and force balances were mechanically connected and the rotation mechanism was part of the balances.

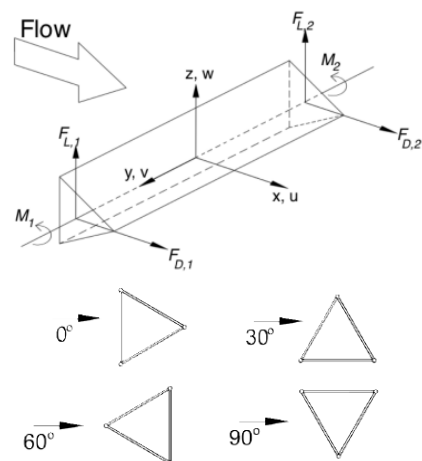


Figure 2. (left) test setup in the CWT for measuring aerodynamic forces on scaled mast sections. (right) Orientation of force and flow components given in a flow-fixed Cartesian coordinate system and definition of different flow angles of attack.

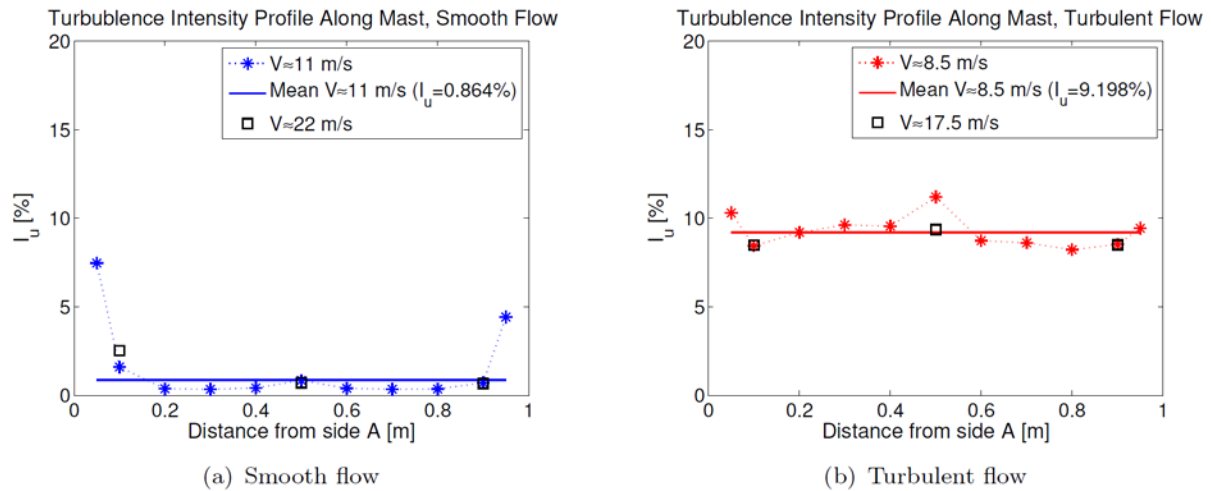


Figure 3. Flow condition with respect to turbulence intensity I_u between end plates. (*left*) smooth flow with an average of $I_u = 0.86\%$ in the core flow and (*right*) turbulent flow with an average of $I_u = 9.2\%$ (side A is the near side of the wind tunnel with windows).

Figure 3 shows the flow condition between the end plates for the two flow types used in the wind tunnel study. The smooth flow reflects the natural flow condition in the wind tunnel but is affected near the end plates by the surface boundary layer. Turbulent flow was generated by installing a grid in the test section and the magnitude of I_u was adjusted by variation of the distance between model and grid. The squares on the graphs in Figure 3 indicate the stability of the turbulence level for higher airspeeds than used in the detailed profile measurements. Due to the increased resistance to the air circulation the maximum wind tunnel airspeed is for turbulent flow 25 m/s whereas for smooth 33 m/s were reached.

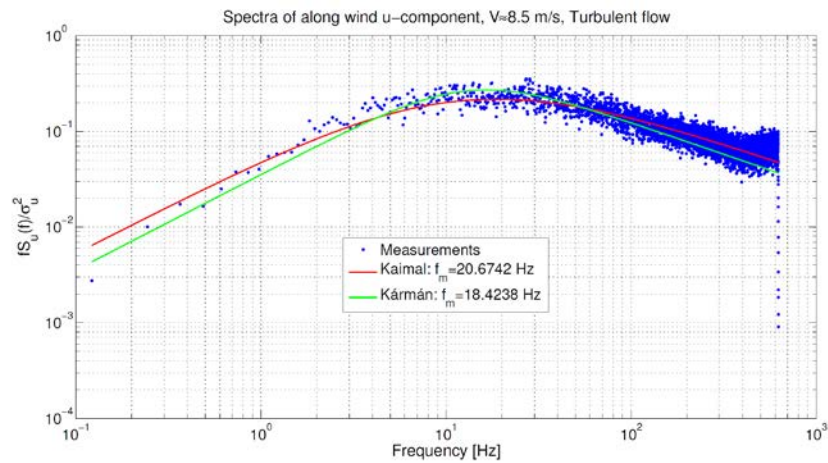


Figure 4. Spectral density of the along wind velocity fluctuation in turbulent flow recorded at 8.5 m/s.

In Figure 4 the spectral density function (SDF) of the along wind velocity fluctuation is shown as the result of using the grid-method to generate a specific level of turbulence. Both, the spectral models of von Kármán and Kaimal have been fitted to the measured SDF. The estimation of the integral length scale, L_{ux} , was based on the Kaimal model indicating a stable value of 0.12 m for different airspeeds.

2.3 Blockage correction

The blockage effect has been calculated based on the ration of the reference cross-sectional area of the model, S , to the cross-sectional area of the wind tunnel, A . In frame of this study S is defined as the projected area of the mast section individually calculated for each angle of attack, α . Consequently the blockage ratio varies over α . Mast type 1A has the lowest maximum blockage with 2.9% and mast type 1C the largest with about 5.2%. Using Cowdrey's method [4] for correction of the measured drag forces the corresponding maximum blockage-related reduction of the forces was for mast 1A 3.8% and for mast 1C 6.8%.

2.4 Parameter definitions

To compare the results from wind tunnel measurement to literature and codes, predicted drag coefficients have been calculated according to the different methods taking as much information of the test conditions (angle of attack, turbulence intensity, etc.) into account. The drag coefficient is generally defined as

$$C_D = C(D) = \frac{2 \cdot F_D}{\rho_{air} \cdot A \cdot V^2} \quad (1)$$

Where F_D is the measured drag force, V the mean wind speed, ρ_{air} the air density and A is the mast reference area. For all here presented methods the reference area is defined as the enclosed area A_{en} as shown in Figure 1 and is kept constant for all angles of attack.

The predicted aerodynamic drag coefficient can be calculated according **NMI** as follows:

$$C(D) = C(C)_T + C(D)_S \quad (2)$$

Where $C(D)_T$ is the drag of the bare structure and $C(D)_S$ the contribution from the ancillaries. For square and equilateral triangular mast configurations the drag coefficient is given as follows:

$$C(D)_T = \frac{C(D)_f \cdot A_f \cdot K(\alpha)_f + C(D)_r \cdot A_r \cdot K(\alpha)_r}{A_f + A_r} \quad (3)$$

Here all “ f ” indicated quantities refer to flat-sided members and “ r ” to tubular or rounded members. A is the total projected area normal to the face of the respective members and $K(\alpha)$ are wind direction factors for the different member types. For tubular members $K(\alpha) = 1$.

The estimation method provided by **EC3** [5] bears strong similarity to the **NMI** approach where the overall drag force coefficient c_f consists of a contribution from the bare structure, $c_{f,S}$, and from the ancillaries, $c_{f,A}$:

$$c_f = c_{f,S} + c_{f,A} \quad (4)$$

Equation (5) shows the composition of the drag force coefficient on the example of a single braced frame:

$$c_f = c_{f,f} \frac{A_f}{A_S} + c_{f,c} \frac{A_c}{A_S} + c_{f,c,sup} \frac{A_{c,sup}}{A_S} \quad (5)$$

The secondary indices “ f ” and “ c ” refer to flat-sides and circular members. Furthermore, the **EC3** distinguishes between circular members in the subcritical and supercritical range (“ sup ”). The ranges are separated at $Re = 4 \cdot 10^5$ omitting conservatively the existence of the critical range. In the determination of the different force coefficients contributions the solidity ratio φ is required where A_S is the total projected area when viewed normal to the face of the bare structure:

$$\varphi = A_S / A_{en} \quad (6)$$

Like the Eurocode the Engineering Science Data Unit (**ESDU**) provides an approach to estimate the wind force coefficient of lattice structures. In comparison to **EC3** the **ESDU** method takes more boundary condition into account such as the surface roughness of the structural elements, the turbulence intensity in the approaching airflow. Depending on whether the structure consists of circular elements, flat-sided or a mixture of both the approach is slightly varied in its formulation. Generally, the total drag coefficient is defined as

$$C_{D,tot} = C_D + \Delta C_D \quad (7)$$

Where C_D is the contribution of the bare structure and ΔC_D derives the ancillaries. The drag of the bare structure is

$$C_D = C'_{D1} \cdot f_D \cdot f_\varphi \cdot f_s \cdot f_\alpha \quad (8)$$

Here, C'_{DI} is the uncorrected value of the drag coefficient, f_D a correction factor of the diameter ratio in the lattice frame, f_ϕ the influence factor of the solidity ratio, f_s the shielding/interference effect factor of the forward frame on those downstream at $\alpha = 0$ degree and f_α is the correction factor for the angle of attack. The architecture of all three presented methods is quite similar. Occurring differences in the prognosis of the drag coefficient will hence mainly derive from differences in the underlying graphs providing input values for the estimation methods.

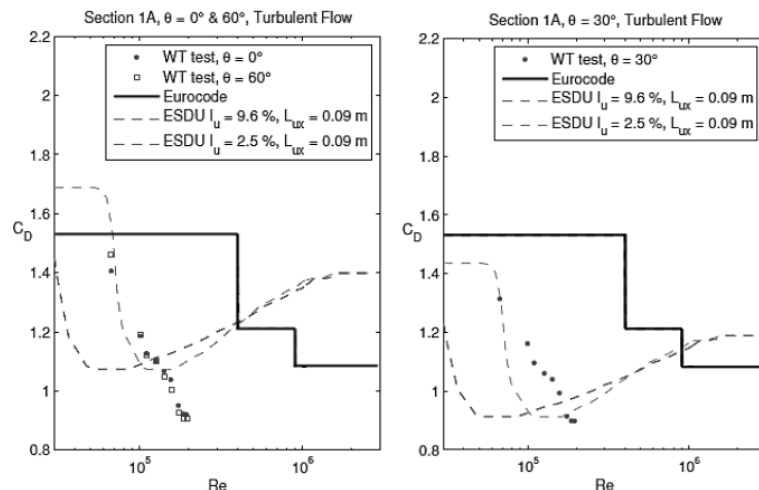
The Reynolds number used in the graphs is calculated as the chord-based Reynolds number Re_c where V is always the time averaged value of the approaching wind and D_c is the chord member diameter:

$$Re = Re_c = \frac{D_c \cdot V}{\nu_{air}} \quad (9)$$

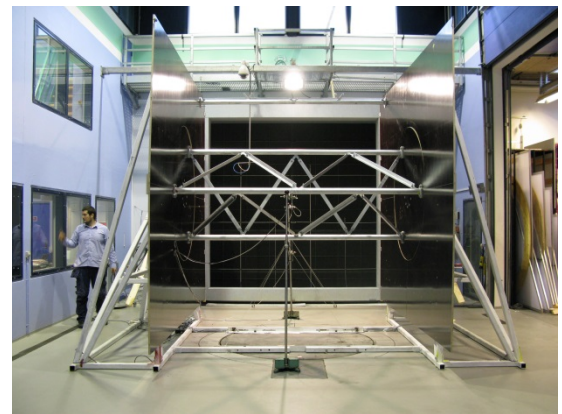
3 TEST RESULTS

3.1 Full-scale wind tunnel testing (reference data)

For the full-scale wind tunnel study two types of original mast segments have been tested in the VELUX wind tunnel. The mast segments were 3m long and suspended horizontally on rotating discs integrated in end plates on either side of the section (Figure 5, right). Both mast types are of equilateral triangular cross-section with legs of circular tubes but different in making of the bracings: mast 1 has tubular bracings and mast 2 bracings with L-shape cross-section. The present study focuses on tubular bracing for comparison between full size and model scale.



Reynolds-dependent drag coefficients in turbulent flow on mast type 1 without additional installations. 0 and 60 degrees angle of attack (left) and 30 degrees (right) [1].



Experimental setup of the full-scale wind tunnel test in smooth flow on mast type 2 with L-shaped bracings (looking upstream)

Figure 5. Results and test setup from full-scale study.

The wind loads have been studied under two test conditions: low turbulent flow, here referred to as ‘smooth flow’, with a longitudinal turbulence intensity of 1.1% and turbulent flow with 9.6% turbulence intensity. Figure 5 (left) shows an example of the results (dots) from the full-scale study [1] on a mast section with exclusively tubular members (legs and bracings) in turbulent flow. Compared to the load coefficients from Eurocode 3 [5] and from ESDU ([6],[8]) the measurements are significantly lower than the codified loads and for some flow directions even lower than predicted by the detailed items from ESDU.

3.2 NMI repetition study

The NMI mast has been tested in two different flow conditions (smooth and turbulent) and for different angles of attack. The flow conditions in the repetition study are documented in chapter 2.2 and the initial study in 1977 is described in [2]. However, no turbulence level is given for smooth flow condition in the original test.

The main purpose of repeating the NMI study was to see whether the chosen test setup of the new study (comprising model construction, flow condition and data acquisition chain) provides comparable data to the initial study. If the assumption that the NMI study influenced the formulation of modern codes is sound, the degree of reproducibility defines how directly the results from the Rambøll mast can be related to codified load coefficients. Comparing the results for smooth flow (not shown as graph) the replicated results are 8 to 10% higher compared to the initial study, depending on the angle of attack. For turbulent flow the difference is significantly smaller (Figure 6): for 0 and 60 degrees the initial and repetition study are still about 10% off but for 30

and 90 degrees both studies show practically the same result. Since turbulent flow is for structural design purpose considered more relevant the repetition of the NMI results is fully acceptable. The observed differences for some angles of attack may be due to craftsmanship of model design but this hypothesis remains speculative.

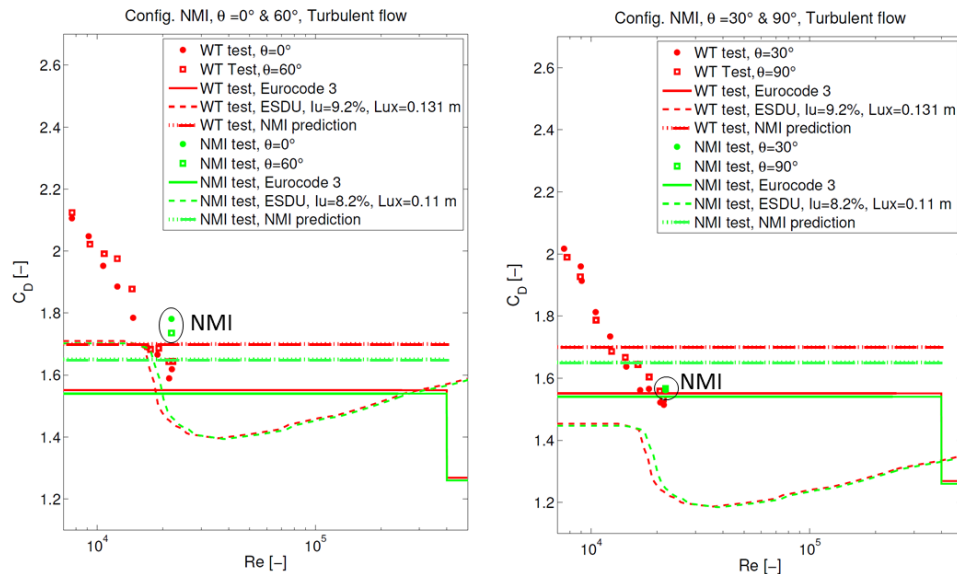


Figure 6. Comparison of the replicated NMI study to the originally reported results and to estimated drag values from literature and codes.

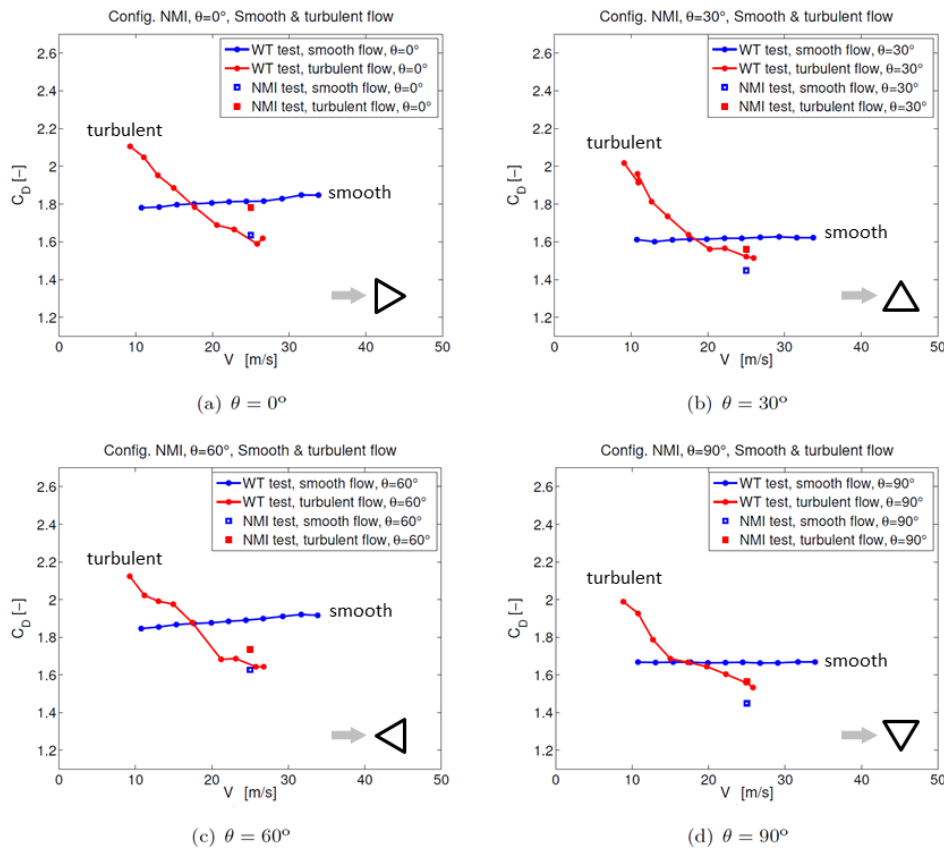


Figure 7. Comparison of the replicated NMI study to the originally reported results separated after angle of attack.

Most remarkable difference between both studies is that the NMI study consistently reports higher drag coefficients for turbulent than for smooth flow, whereas the repetition study shows for that exact airspeed the opposite.

3.3 Bare structure mast (1A)

In the following the Rambøll mast structure studied at full size [1] was tested at reduced scale 1:6 in smooth and turbulent flow. In smooth flow (Figure 8) the measured drag coefficient remains practically constant since all structural members remain in the subcritical range. Before reaching the critical range the full size values are very consistent with the results from scaled testing. For 0 and 60 degrees the measured results align along the NMI estimation model and for 30 and 60 degrees the measured values align along the EC3 model.

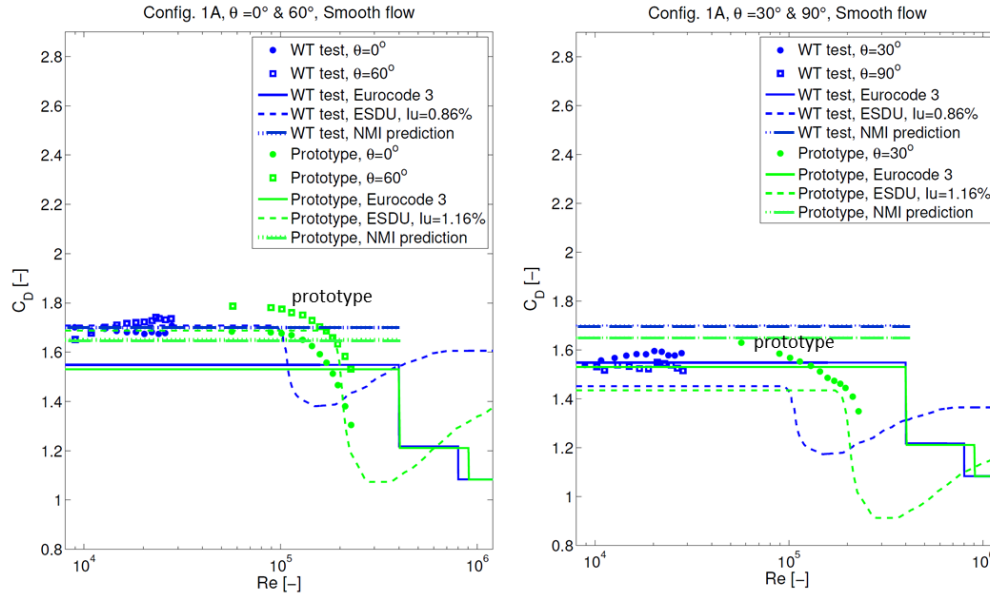


Figure 8. Comparison of the Rambøll mast (1A = bare structure) tested at reduced scale in smooth flow to the results from full size study and to estimated drag values from literature and codes.

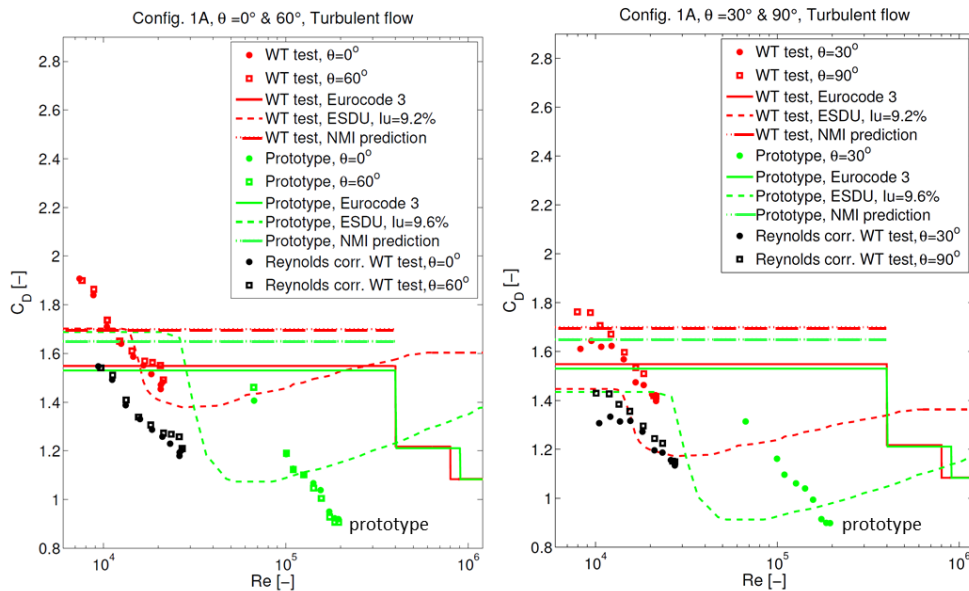


Figure 9. Comparison of the Rambøll mast (1A = bare structure) tested at reduced scale in turbulent flow to the results from full size study and to estimated drag values from literature and codes.

Figure 9 shows the results from turbulent flow. Both drag coefficients from full size and scaled wind tunnel tests enter the critical range and exhibit the typical decrease of C_D with increasing Reynolds number. The full size tests however indicate a larger drop of the load coefficient than the scaled model study but that is primarily because of the airspeed limit of 25 m/s in the scaled model test. Otherwise the difference between full and reduced scale might be smaller.

On the results from the scaled model in turbulent flow a correction concept has been applied based on the notion that models consisting of tubular members at reduced size show, depending on the geometric scale and Reynolds range, too high load coefficients in the study. This deficiency can to a certain degree be bypassed in the model design by reducing the diameter of the members (geometrically off-scale). The smaller body experiences hence a lower aerodynamic drag force F'_D yielding, when applying equation (1) with the initial (on-scale) value for model reference area A_M , to a smaller force coefficient. This geometrical correction is expressed in equation (10):

$$A'_M = A_M \frac{C_{D,FS}}{C_{D,M}(Re)} \quad (10)$$

A'_M is the modified off-scale model reference area (diameter since the length of the members doesn't change), A_M is on-scale model reference area, $C_{D,FS}$ is the expected drag coefficient in full-scale for the characteristic wind speed and $C_{D,M}(Re)$ is the expected model drag coefficient depending on the adjusted wind tunnel airspeed (= resulting Reynolds number). For estimating the expected drag coefficients in model and full-scale ESDU Item 80025 [7] has been used. In smooth flow the drag curve indicate subcritical range where $C_{D,FS}$ and $C_{D,M}$ are identical and require hence no correction.

The correction displayed in the graphs is only indicative since the used 1:6 model is considered being a modified version of an intended 1:5 model. This is a fair assumption with respect to the diameters of the mast members but the lengths should reflect a 1:5 scale and are hence too short. The corrected values for the drag coefficients in Figure 9 indicate a certain but not complete compensation of the insufficient Reynolds similarity. At least show the corrected values a larger consistency with literature than the uncorrected values exceed the literature values significantly for lower Re-numbers.

3.4 Mast with latter (1B)

Figure 10 shows the drag coefficients for Rambøll mast with ladder in turbulent flow. The Reynolds-corrected drag coefficients are similar to the results from the full size study but occur at different Reynolds numbers. The model scale values correspond in the case to the drag curves predicted by ESDU whereas the full size values occur in this case at significantly higher Reynolds numbers, i.e. wind speeds. This mismatch hampers the usability of the results for structural design since the model scale data and literature cannot exactly predict the wind velocity at which the drop of C_D actually happens at full size, even not under consideration of numerous boundary conditions (ESDU). For that reason the envelope curve given by EC3 needs to be conservative to cover this and other inaccuracies.

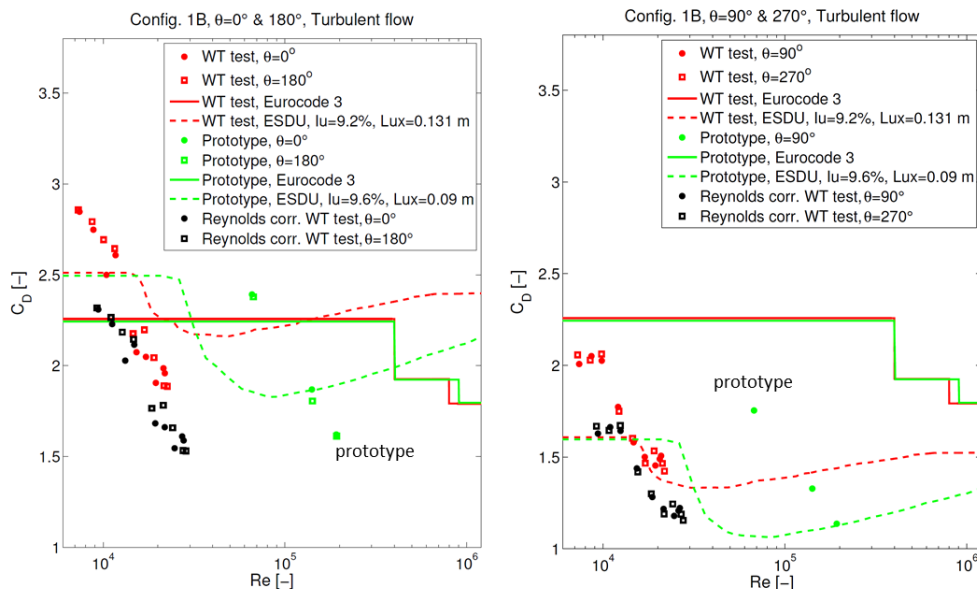


Figure 10. Comparison of the Rambøll mast (1B = structure & ladder) tested at reduced scale in turbulent flow to the results from full size study and to estimated drag values from literature and codes.

3.5 Mast with ladder and feeders (1C)

For the Rambøll mast with ladder and antenna cables (feeders) the Reynolds corrected drag coefficients start underestimating the values obtained from the full size study (Figure 11). Again, this picture is incomplete due to the limitation of wind tunnel airspeeds and might be more consistent if unlimited air velocity would be available. As in the preceding cases the ESDU predicted drag curve seem to be well consistent with the data from wind tunnel tests on the scaled model, whereas the full size

values are only similar in magnitude but occur at much higher Reynolds number. This observation supports the suggestion made at the beginning of the study that codified load data, in this case the ESDU data base, is built upon data from wind tunnel studies performed on lattice masts at reduced scale. This is as such not surprising since wind tunnel tests on scaled models is the backbone of wind load studies for structural design. This (re)finding becomes in that way relevant for the investigation that the wish from industry to save money and material through more accurate load data is impeded by the difficulty to determine when, in terms of wind speeds, the load reduction applies.

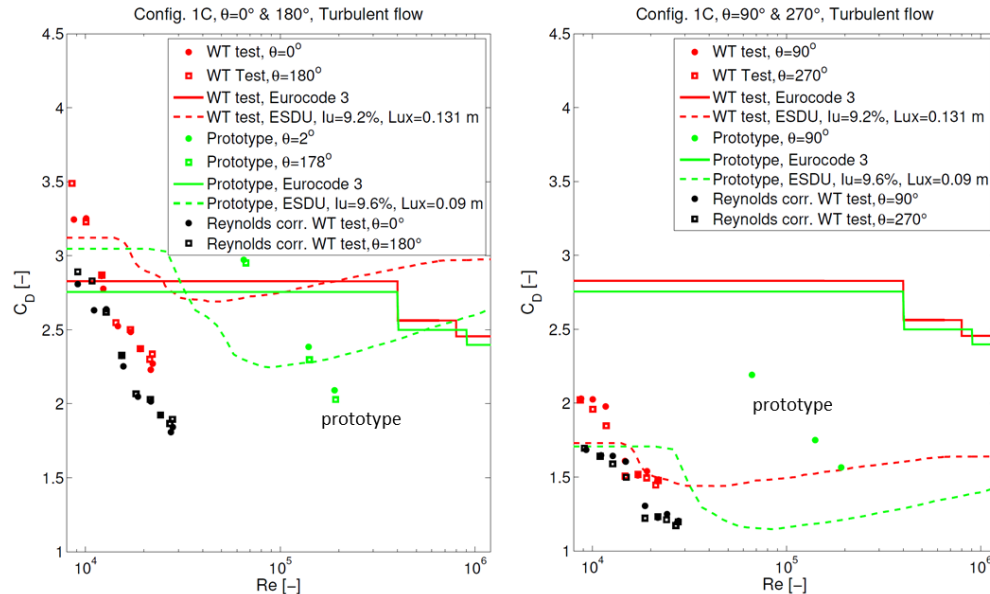


Figure 11. Comparison of the Rambøll mast (1C = structure & ladder & feeder) tested at reduced scale in turbulent flow to the results from full size study and to estimated drag values from literature and codes.

4 SUMMARY & CONCLUSION

Lattice mast structures have been investigated regarding their aerodynamic drag behavior through wind tunnel tests on models at reduced scale in smooth and turbulent flow. These results have been compared to data from studies at full size and from literature. The main findings from the study are:

- The results from an early study assumed to form the basis for codified wind load coefficients could be replicated with sufficient accuracy. This strengthens the comparability between the results from the main study and codified loads.
- Differences between wind load coefficients derived from wind tunnel tests on full size structures and on models at reduced scale manifest in the coefficient magnitude but moreover on the wind velocity range (Reynolds number) at which they occur.
- It seems that some codified data reflect the aerodynamic behavior of model scale force coefficient rather than the behavior in full scale. This fact requires from the codification point of view a conservative envelope curve to cover this and other uncertainties.
- With respect to the desire from the industry to save money and material through more accurate load data the determination of Reynolds number for the load coefficients drop is the main challenge. So far, only full size test can provide the required information to specify the aerodynamic behavior of the wind load accurately.

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